IMPACT OF PAST, PRESENT AND FUTURE WIND TURBINE TECHNOLOGIES ON TRANSMISSION SYSTEM OPERATION AND PERFORMANCE

PIER PROJECT REPORT

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Impact of Past, Present and Future Wind Turbine Technologies on Transmission System Operation and Performance

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission) conducts public interest research, development, and demonstration (RD&D) projects to benefit the electricity and natural gas ratepayers in California. The Energy Commission awards up to $62 million annually in electricity-related RD&D, and up to $15 million annually for natural gas RD&D.

The PIER program strives to conduct the most promising public interest energy research by partnering with RD&D organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

· Buildings End-Use Energy Efficiency

· Industrial/Agricultural/Water End-Use Energy Efficiency

· Renewable Energy Technologies

· Environmentally Preferred Advanced Generation

· Energy-Related Environmental Research

· Energy Systems Integration

Impact of Past, Present and Future Wind Turbine Technologies on Transmission System Operation and Performance is the final report for Task 1 for the PIER Intermittency Analysis Project (IAP), contract number 500-02-004, work authorization number MR-017, conducted by the IAP team comprised of the California Wind Energy Collaborative, Exeter Associates, BEW Engineering, Davis Power Consulting, and GE Energy Consulting (with assistance from AWS Truewind, NREL, ORNL and Rumla Consulting). The information from this project contributes to PIER's Renewable Energy Technologies program.

For more information on the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier or contact the Energy Commission at (916) 654-5164.

Abstract

The Intermittency Analysis Project (IAP), funded under the California Energy Commission's Public Interest Research (PIER) Program, was undertaken to assess power system impacts resulting from the implementation of California's Renewable Portfolio Standard (RPS). Given the current state of commercial viability of the various renewable energy technologies, it is envisioned that RPS goals will be achieved largely through significant increases in the state's installed base of wind energy facilities. The preparation of this report was the first task of this system impact assessment.

The objective of this task was to provide technical context on wind energy technology for those parties involved in the intermittency analysis effort. In this document, the electrical characteristics of modern-day wind turbines and the impact of those characteristics on electric power transmission system planning and operation are emphasized. The evolution of utility-scale wind turbine technology and wind plant development over the past 25 years, with an emphasis on the electrical impacts related to performance, reliability, power quality and operation of the interconnected transmission network, are described. This report expands upon previous CWEC reports by focusing on the electromechanical conversion of wind energy to electrical energy, from the wind turbine gearbox output shaft to delivery of energy to the bulk power transmission network.

Keywords

Section 1 - Introduction and Scope

The purpose of this document is to provide technical context on wind energy technology for those parties involved in the intermittency analysis efforts being undertaken to support the anticipated near term increases in wind generation capacity in California. These increases in wind capacity are being driven by the state's implementation of its Renewable Portfolio Standard (RPS) authorized under SB 1078. In this document, the electrical characteristics of modern-day wind turbines and the impact of those characteristics on electric power transmission system planning and operation are emphasized.

This document describes the evolution of utility-scale wind turbine technology and wind plant development over the past 25 years with an emphasis on the electrical impacts related to performance, reliability, power quality and operation of the interconnected transmission network. The target audience for the paper is the engineer with some basic familiarity with electric power systems and the transmission planning process, but with little or no background in wind energy conversion technology and its impact on the grid. Prior Energy Commission[i] and CWEC[ii] reports have provided technical background on the aerodynamic and mechanical aspects of modern wind turbines, including the turbine rotor (blades) and drive train, up to and including the gearbox. This report expands upon that body of work by focusing on the electromechanical conversion of wind energy to electrical energy, from the gearbox output shaft all the way to the bulk power transmission network.

The scope of this document is limited to utility scale wind plants with interconnections at the high voltage transmission level. Neither residential scale wind turbines nor wind turbine "clusters" connected at primary distribution level are addressed. These applications are not anticipated to have significant operating impacts on California's bulk power transmission system. Further, interconnection issues with these applications are being addressed by the Commission through its involvement with the CPUC Rule 21 technical and policy working groups.

The balance of the report is organized into six additional sections, as follows:

> *Section 2 - A Brief History of Wind Power Development in California*. This section provides historical context for the current state of wind integration within California's electric power transmission system.

> *Section 3 - Historical Transmission and Interconnection Issues at California's Major Wind Development Areas*. Transmission and interconnection issues which occurred in conjunction with the

interconnection of California's early wind plants are reviewed. In addition, problem solutions, either through specific wind facility modifications or through wind turbine technology improvements, are presented.

Section 4 – Present Day Wind Energy Technology Review. This section provides an overview of modern wind turbine technology, with a particular emphasis on electrical characteristics. Wind turbine electrical topologies and their impacts on grid integration are examined.

Section 5 – New Transmission and Interconnection Issues for High Wind Penetration Scenarios. California's current modest level of penetration of wind power has resulted in such minimal impacts to the transmission system that wind generation receives presently little or no consideration in the planning and operations of the state's transmission network. With the penetration levels envisioned under the RPS, wind will be a significant component of generation in the state, and additional considerations for planning and operational studies will be an absolute necessity. This section describes additional transmission impacts that will accompany these higher penetration levels.

Section 6 – New and Evolving Wind Power Interconnection Standards and Procedures. Interconnection practices and regulatory processes have changed significantly in the time since most of California's existing wind capacity was commissioned. This section provides an overview of these evolving standards and practices and their potential impacts on future wind project interconnections in the state.

Section 7 – Future Wind Turbine Technology Enhancements for Improved Grid Compatibility. The final section describes wind turbine technology enhancements that are already under development to improve the performance of wind power with respect to transmission system operational impacts. California will benefit from these technology developments, which are being driven largely by grid compatibility needs in areas (primarily in Europe) already experiencing penetration levels similar to those anticipated under the California RPS.

Section 2 – A Brief History of Wind Power Development in California

The OPEC oil embargo of the early 1970's, and the high oil and gas prices that followed it, sparked a rebirth of interest in wind power, as well as other renewable energy sources in the US. During this period, the U.S. Department of Energy increased funding for wind power research and development, and a series of megawatt- and multi-megawatt prototype wind turbines were installed in research and demonstration projects throughout the country. These machines turned out to be ahead of their time, and suffered through numerous mechanical and structural failures before the DOE program, as well as the wind "industry" (to the extent one existed), gravitated towards development of smaller (50 to 300 kW) machines in the latter part of the decade.[iii] But it was California's "Wind Rush" of the early 1980's that remains universally acknowledged as the beginning of the modern commercial wind industry. The impetus for this rush of development was a convergence of economic and regulatory drivers, including:

> Passage of the Public Utility Regulatory Policy Act (PURPA) in 1978, mandating purchases of electricity by regulated utilities from certain qualifying facilities (QFs) at the utilities' avoided costs, and, further, exempting these QFs from state and federal regulation as public utilities;
> High fossil fuel prices, and expectations of even higher future prices causing regulators to view the utilities' avoided costs as the forecasted cost of new coal, oil and gas fired power generation;
> State mandating of Standard Offer 4 (SO4), long-term (20- to 30-year) contracts that offered 10 years of fixed, above-market feed-in tariffs similar to what exists now in many European markets;
> And, finally, combined federal and state investment and energy tax credits, at least prior to 1985, which resulted in an effective tax credit of nearly 50 percent.

The net result of the convergence of these drivers was the installation of over 17,000 wind turbines, with a total capacity of over 1600 MW, and the birth of the "wind farm" concept. Wind farms are defined as large groupings of wind turbines connected to a single point of interconnection at transmission levels. Turbines are connected through the facility's own power distribution (or "collection") system with typical aggregated power ratings in the tens to hundreds of megawatts. By 1988, only six years after the first SO4 contracts took effect, California became home to over 90% of the world's installed wind capacity.

The overwhelming majority of this wind capacity was installed in the three geographic areas shown in Figure 1,[iv] the Altamont Pass in eastern Alameda and

Contra Costa Counties, the Tehachapi Pass in Kern County, and the San Gorgonio Pass in Riverside County.[v]
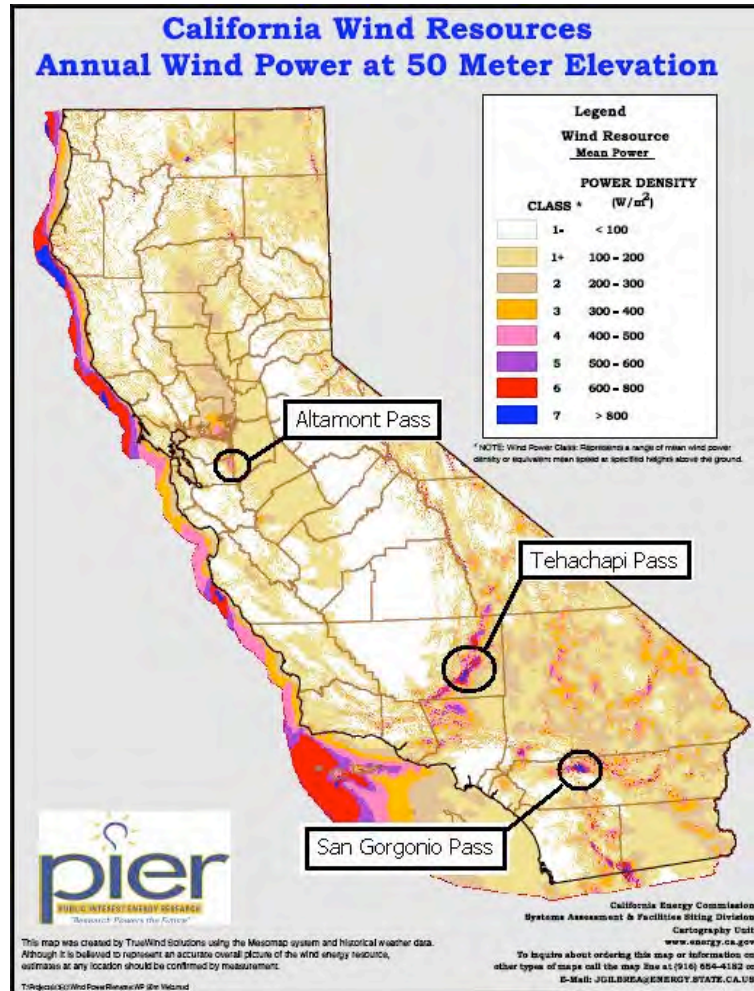
Figure 1. Major Wind Development Areas in California

These three major areas of development had in common a combination of two factors that attracted project developers. First, each had a good and predictable wind resource driven primarily by thermally-induced winds resulting from cool coastal air being drawing through the pass as warm air heated the floor of the valleys and deserts. Second, each location was traversed by existing high voltage transmission lines, which, at least at that time, were underutilized to one degree or another.

The Altamont Pass, though not blessed with the best wind resource, is home to Pacific Gas & Electric's (PG&E) Tesla Substation, the heart of northern California's bulk power transmission system. The presence of numerous 115 kV and 230 kV transmission lines terminating at Tesla allowed wind developers to

place their wind plant substations immediately adjacent to PG&E right-of-way, minimizing transmission interconnection costs. In contrast to the Altamont Pass, the Mojave Desert gives Tehachapi some of the best thermal winds in the state. However, it is located on the northern edge of Southern California Edison's (SCE) system, with a relatively weak 66 kV transmission system in the area.

The wind rush came to an end in the late 1980's, being brought to a conclusion by the phasing out of the tax credits between 1984 and 1986 and the prohibition on new SO4 contracts in 1988. Wind development in the state has been largely stalled for nearly two decades as a result of both state and federal regulatory changes. An exception is re-powering projects which replace the hastily designed and installed wind rush machines, many which failed soon after commissioning during the boom years.[vi] Nevertheless, the world's first laboratory for investigation of grid impacts of large scale wind power development had been formed in these California mountain passes.

Figure 2. Wind Farm in San Gorgonio Pass

(Photo: Warren Gretz, NREL)

Section 3 – Historical Transmission and Interconnection Issues at California's Major Wind Development Areas

Grid interconnection and transmission problems that occurred during California's wind power boom of the 1980's are not widely documented. Perhaps this is understandable, since it was not in the best of interest of the utilities, regulators or wind plant developers to publicize these problems. To the authors' knowledge, the best records of problems that did occur and the solutions that were implemented to overcome them are safely tucked away in the file rooms of the utility companies and wind plant operating companies (many of them, now defunct) that resolved them. However, a second and more important reason for the lack of publicly available documentation on these problems is the very lack of problems, or at least their lack of severity, in the first place, which allowed for quick and inexpensive "fixes", where needed. This is confirmed in one of the few publicly disseminated papers on the topic.[vii] Putnam's investigation, conducted by interviewing operating personnel involved with wind plant integration at both PG&E and SCE in 1995, focused on the following issues:

Reactive Power Control and Voltage Regulation: The constant speed induction generator based wind turbines installed in the state in the 1980's represented large reactive loads to the grid. This reactive load, which consists of both a fixed and a variable component, is further described in Section 4. This reactive power consumption created two problems for both the PG&E and the SCE transmission systems. First, the reactive current created unnecessary loading and losses in the transmission system; and second, this reactive current created a voltage drop which violated planning and operational voltage regulation criteria, particularly in the Tehachapi Pass area. PG&E and SCE chose to mitigate these problems differently due to the difference in strength of the network at Altamont and Tehachapi and due to the different problems that resulted.

As voltage regulation at the transmission level was less of an issue in the Altamont Pass, PG&E began requiring that the revenue meters at each wind farm record kilovolt-ampere-hours (kVA-hr) in addition to the kilowatt-hours (kW-hr) on which the feed-in tariff was paid. Excessive reactive power consumption, which was reflected in the difference between the kVA-hr and kW-hr meter registers, was subject to financial penalties to compensate the utility for the increased loading and line losses caused by this reactive consumption. The penalties were structured such that nearly all of the wind farm operators in the pass retrofitted their turbines and/or wind plant substations with power correction capacitors.

The Tehachapi Pass, with as much wind capacity as in the Altamont, more energetic winds, and its location on the edge of SCE's transmission system, was more problematic. The high source impedance combined with the large amounts of reactive power consumed by the wind turbines resulted in severe voltage regulation problems during periods of high production. SCE determined that the most economic solution to the problem was to curtail wind generation but continue to pay the wind plant operators for the undelivered energy. This arrangement continued until SCE suspended these payments in 2000,[viii] and was aggravated by improved capacity factors resulting from the repowering of projects with newer technology better able than the early-1980's technology to withstand the high winds in the pass.

Harmonics: Voltage harmonics are periodic distortions of the supply voltage which can cause overheating of equipment such as transformers and motors, as well as disturb the operation of sensitive electronics that have been designed to operate from a sinusoidal source. Voltage harmonics result from the flow of harmonic currents generated by nonlinear loads or generators through the source impedance at the location of the nonlinear device.

Power electronic devices (rectifiers, inverters, converters) are commonly associated with current distortion, but ubiquitous power system equipment such as transformers and rotating machines (motors and generators) are also sources of harmonic currents, particularly when they are designed and operated near magnetic saturation. There are no documented cases of problems related to power electronic induced harmonics in California's three major wind development areas, primarily due to the fact that variable speed wind turbines with power electronic converters were not installed in significant number until the mid-1990's. By that time power converter technology had advanced to incorporate high frequency switching, which mitigated the power quality problems associated with 1970's and 1980's converter technology.

There is, however, at least one documented case of transformer-induced current harmonics producing unacceptable voltage distortion at a wind farm in the Tehachapi Pass. The situation was aggravated by the installation of power factor correction capacitors (see *Reactive Power Control and Voltage Regulation*, above), which created a resonance at a low enough frequency to be excited by the non-linear current drawn by the transformers. This was the subject of field measurements and analysis conducted by Muljadi et al.[ix]

Frequency Control and Operating Reserves: Variation in wind generation was small relative to normal variations in load; thus, frequency control was neither an anticipated nor actual problem, even in the highest-wind-generation, lowest-load operating condition. Neither PG&E nor SCE (both operating as vertically integrated utilities at that time) made any changes to their spinning or non-spinning reserve requirements as a result of the wind generation, and neither suffered negative consequences. Clearly, this was due to the modest level of penetration, and this experience has little relevance to the wind penetration levels projected for California's future. These issues are being addressed in detail by other members of the Energy Commission Intermittency Analysis Project team.

Stability: There were no documented system stability problems that resulted from the integration of wind generation into California's transmission network. Putnam attributed this to the large moments of inertia associated with wind turbine rotors and the highly compliant shaft linking the turbine and the generator (relative to conventional turbogenerators). However, the characteristics of the generator technology employed in the wind turbine determine how this inertia is coupled to the electric transmission system, so it is difficult to so broadly generalize about wind's impact on system stability. It is more likely that the low penetration level and the maintenance of sufficient spinning reserve were the primary factors for the lack of problems experienced.

Transmission Line Protection: Wind plant interconnections were often connected as taps to existing high voltage transmission lines, creating multi-terminal lines (three or more terminations). While the protection of multi-terminal transmission lines is complicated in itself[x], the presence of wind generation at one or more terminals created additional challenges. First, a wind plant of constant-speed induction generator based wind turbines is a weak source of fault current relative to equivalently sized synchronous generators. This raised concern about the efficacy of current based protective relaying (e.g., overcurrent or distance relays) for detection of faults on the transmission line from the wind plant terminal. Compounding this problem were the installation of power factor correction capacitors (again, see *Reactive Power Control and Voltage Regulation*, above) and the possibility of islanding due to the self-excitation of these induction generators. The possibility of the self-excited generators keeping the transmission line energized while not sourcing enough short circuit current to activate protection at the wind plant line terminal set up a scenario in which the fault may fail to clear during the period of time between tripping of the remote terminals and the automatic reclosure which occurs a short time after the opening of the remote circuit breakers.

This was a serious reliability concern for the system protection engineers at the impacted utilities.[xi,xii]

The solution to this concern was to install (and to retrofit on earlier projects) direct transfer trip equipment to open the terminal at the wind plant upon detection of a fault at either remote terminal. The transfer trip signal was carried on dedicated leased telephone circuits between the wind plant substation and the substations at the remote ends of the transmission line. To prevent over-voltage damage to wind plant equipment that might occur after such an event, the authors are aware of automatic tripping schemes backed up by UPS power designed to disconnect power factor correction capacitor banks at the wind plant substation immediately upon opening of the main circuit breaker connected to the transmission line.

An additional issue, not addressed by Putnam, is that of voltage flicker:

Voltage Flicker: Voltage flicker is a momentary sag in line voltage, either periodic or aperiodic, that results in perceptible (often annoying) fluctuations in the intensity of light from lamps supplied by a time-varying voltage source. There are three potential sources of flicker associated with wind turbines. The first is due to voltage fluctuations that may occur as a direct result of power fluctuations from the wind turbine under normal operation in turbulent winds. While this effect may be very real with individual wind turbines connected at the utilization or primary distribution voltage, in a utility scale wind plant the spatial diversity of the array of wind turbines results in a statistical filtering of these stochastic fluctuations, such that they are imperceptible at the point of common coupling with the transmission network. This has been confirmed by studies conducted in California following the development of the 1980's,[xiii] as well as in Minnesota with more current technology.[xiv]

A second source of flicker is voltage drop resulting from the magnetizing inrush current that occurs when an induction generator is first electrically connected to grid. When this connection is made at full voltage through a contactor or circuit breaker, the inrush is often several times the full load current of the generator, and can last for several line cycles, enough to be perceptible to the human eye. This effect is magnified when wind plant control systems allow many machines to be brought on line simultaneously. Modern wind turbine technology has largely relegated this issue to the past. Constant and dual speed machines offered in the current market are equipped with "soft starters", power electronic devices that slowly ramp the excitation to the induction generator, which significantly reduces the inrush current, and, hence, the flicker associated

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with startup. Variable speed machines, with their power electronics interfaces, have inherent current limitation capabilities which virtually eliminate inrush.

The third and final source of flicker is due to the tower shadow effect. Each passing of a wind turbine blade by the tower creates a small output power pulsation. On a single wind turbine this three-per-revolution power pulsation may be noticeable. However, for a large wind farm with many turbines, these pulsations are effectively smoothed out at the point of interconnection with the transmission network due to diversity effects.

Putnam's conclusion was that, in California, grid integration of wind "has not been a problem" and that "any issues that have developed … can be addressed by accepted power system procedures and practices." However, this conclusion was based upon field experience that, though the largest scale implementation of grid connected wind power in the world at the time, must be classified as low penetration relative to the levels envisioned under the RPS implementation plan. In higher penetration scenarios, as will be described in Section 5, not only do many of these issues in fact become problems, but new issues that weren't considered during the 1980's development period arise. But first, in Section 4, we examine how advances in wind turbine technology are able to address many of these past and present grid integration concerns.

Section 4 - Present Day Wind Energy Technology Review

In this section, a discussion of historic and current wind turbine drive train technologies is provided. This includes discussions of the mechanisms and characteristics of generator torque production and generator electrical characteristics. Torque characteristics are discussed in relationship to other turbine subsystems such as the pitch system in pitch regulated machines which leads to a brief discussion of turbine mechanical loads. Also, methods of turbine electrical interconnection, their impact on windplant collection systems and utility distribution systems, are discussed.

Constant Speed Wind Turbines

For many years, the constant speed wind turbine has been the workhorse of the industry. In the early to mid 1980's, thousands of constant speed machines populated the three major wind plants in California. Constant speed architectures are still being applied in the industry today. However, for reasons to be discussed later in this chapter, their popularity is giving way to variable speed machines. A drive train schematic of one common constant speed architecture is shown in Figure 3, below.
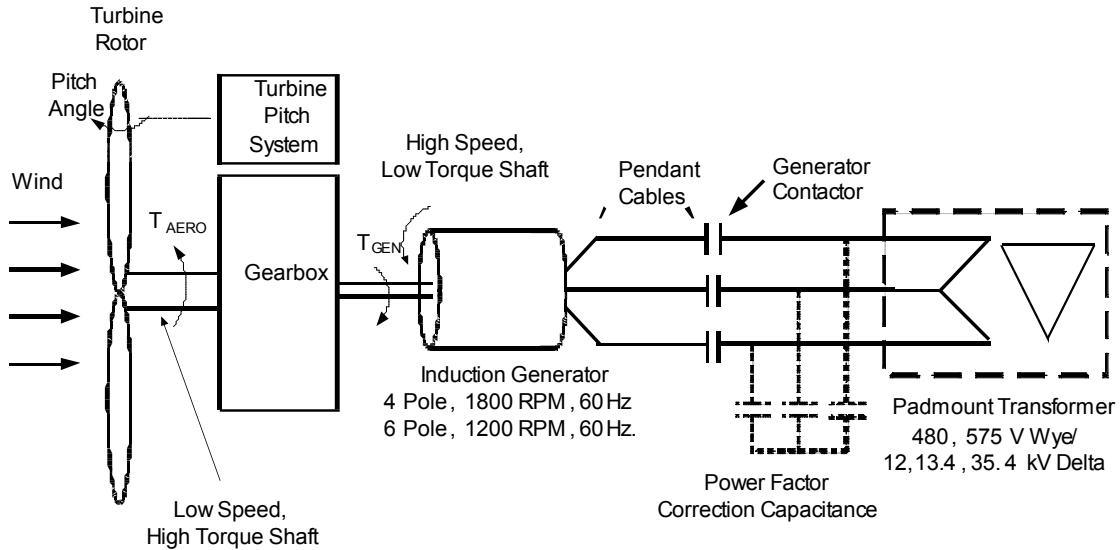
Figure 3. Constant Speed Wind Turbine System

In this figure, turbulent wind at an arbitrary average wind speed is shown exciting the rotor of a constant speed turbine. This wind interacts with the turbine rotor to produce aerodynamic torque, T_{AERO} on the low speed, high torque shaft. This torque is transmitted through the gearbox which serves to increase the speed to match that of the generator shaft. In the ideal case the speed is increased proportionately according to the gear box ratio and the torque is reduced in the same proportion. In reality, there are losses in the gearbox that cause deviation from this ideal relationship, but efficiencies are quite high and the relationship is a good first approximation. The gearbox is added for compatibility with the large base of commercially available industrial 4-pole and 6-pole induction machines that can be purchased at competitive prices. Many early turbines were fielded with off-the-shelf induction motors that were simply run as generators. On the high speed, low torque shaft, the generator torque, T_{GEN}, is shown as reacting the aerodynamic torque. At constant speed, these torques must be equal and opposite or the machine will accelerate or decelerate. The induction generator has an inherent torque-speed curve which fits into the wind turbine application quite naturally. These characteristics are shown in Figure 4.

The electrical output of the generator is shown to the right of the generator in Figure 3 with a three phase connection to a ground-level turbine padmounted transformer. This connection is typically at low voltage class levels, i.e. 600 VAC in North America per the National Electric Code (NEC) and 1000 VAC in Europe per the relevant IEC standards. This connection can be accomplished at low voltage because it is a rather short run. Pendant cables running down the tower

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were typically 80 to 140 feet in length during the early 1980's and today reach levels of 240 feet. The low voltage system is also advantageous because it requires a lower level of training for maintenance personnel than would be required for medium voltage equipment.

The role of the padmounted transformer is to connect the turbine to a wind plant collection system which typically operates at medium voltage. Early wind plants often used a 12 or 13.4 kV medium voltage collection system. Today, wind plants are being installed commonly with a 34.5 kV collection system. The collection system is at medium voltage because this point in a windplant is carrying much larger power levels (from multiple turbines) and this power is being shipped over long distances - miles in the case of large wind plants. In early installations with small kW rated turbines, it was common to have one centrally located padmounted transformer serving multiple turbines. As time has passed and turbines have grown in kW rating, it is now more common for each turbine to have its own padmounted transformer.

Power factor correction (PFC) capacitors are shown as dotted lines in Figure 3. The vast majority of turbines installed in California in the 1980's were initially installed without PFCs. The connection of the induction generator as shown results in main field excitation or absorption of VArs at the turbine as discussed in previous chapters. The VArs absorbed by the generator vary slightly with generator output, but, in the simplest case, can be considered constant over the entire generation range. As discussed in Section 3, it was the installation of these turbines without PFC that created the first noticeable interconnection problem with wind plants in California. The VAr absorption created voltage regulation problems to some extent on the transmission system at all three of California's major wind plants, but particularly in the Tehachapi area. As a result of this problem, installed turbines were retrofitted with PFCs in the mid to late 1980's. In most cases, PFC was added directly at the turbine, as depicted in Figure 3. At times, this was supplemented with additional PFC at the windplant interconnect substation. Since about 1990, constant speed turbines have been supplied with PFC as standard equipment and interconnection agreements have included a VAr or power factor requirement absent from early installations.

Constant Speed Turbine Generator Characteristics

As mentioned earlier, the induction generator shown in Figure 3 is inherently well suited for wind turbine operation. This can best be described by the induction machine's torque-speed characteristics shown in Figure 4. In Figure 4-A, the induction generator torque is plotted against speed. Motoring operation is identified with positive speed and positive torque, i.e. these quantities are rotating in the same direction. Generator operation is identified as negative torque and positive speed or when the two quantities have opposite rotational direction. The

synchronous speed is identified in the figure and this is the operating point where the machine is not producing torque or power.
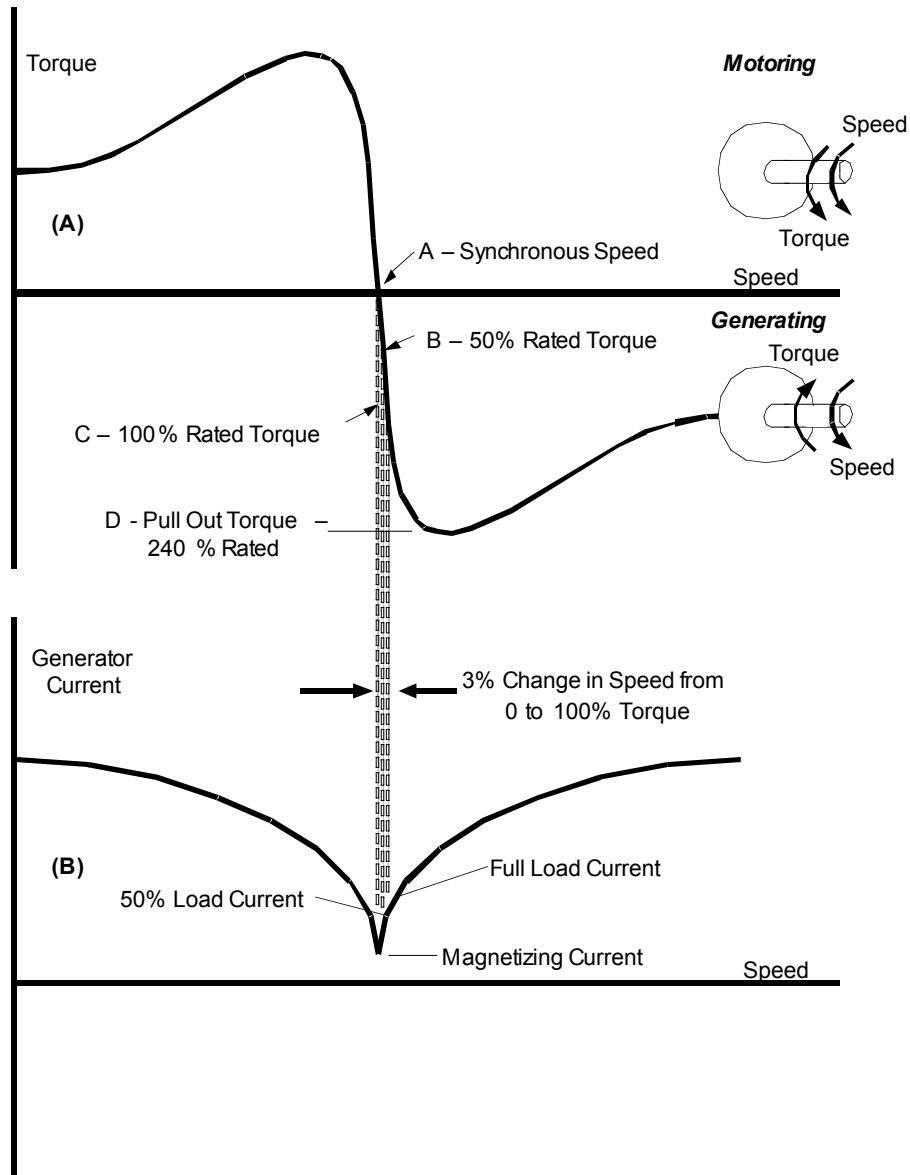
Figure 4. Constant Speed Wind Turbine Torque-Speed Characteristic (A) and Current (B)

Assume for a moment that the machine is operating at point A with the turbine on-line and the generator connected to the utility. As wind speed increases, the aerodynamic torque increases. This causes the generator rotor to accelerate in speed, moving to point B on the torque-speed curve. At this point, the torque has increased to the 50% level and the speed has increased only 1.5% (in this

example). In this case the power has increased to approximately 50% of its rated level. If the wind speed increases further, the turbine will move from point B to point C, which is the rated operating point of the turbine, or 100% torque. As these different operating points are reached, the corresponding generator current can be seen in Figure 4-B. Notice that at the synchronous speed point, A, (no torque, no power), the current reaches its minimum non-zero value. This current level corresponds to the excitation current of the generator which represents the lagging VArs discussed above. Furthermore, while this design is referred to as a constant speed machine, it can be seen that this is not precisely true. Generating torque is proportional to the difference between actual speed and synchronous speed; this term is often used and is referred to as the "slip" of the machine. In the example of Figure 4, the generator is a 3% slip machine meaning that the full load generating speed is 3% above the generator's synchronous speed. This is a distinguishing feature between induction and synchronous generators. Synchronous generators must run at precisely their synchronous speed, proportional to utility frequency. Synchronous generators have been attempted on constant speed machines, but have proven difficult to control for exactly this reason.

Between zero and the rated power of the turbine, the pitch of the rotor blades remains fixed at an angle corresponding to the maximum power or "full power pitch" angle. This is the simplest operation. A more interesting case to consider is when the turbine is operating at rated power in turbulent winds. In this case, the pitch system dynamics become very important in the turbine operation. Assume the turbine is operating at point C, rated power, and a gust of wind occurs. The aerodynamic torque increases and accelerates the generator rotor causing the generator to move towards point D on the curve. This represents a momentary overload condition. As this is occurring, the pitch system attempts to bring the rotor pitch angle to a less aggressive angle of attack which sheds aerodynamic torque. This causes the rotor to slow down relieving torque and power from the generator and the turbine. The pitch system cannot respond quickly enough to prevent this overload condition, but it is fast enough to cause such conditions to exist for only short periods of time. From the torque-speed curve, it can be seen that at worst case, approximately 240% torque and power can be achieved from the inherent characteristics of the generator. In practice, this would be considered extreme. However, overload levels of 25%–50% are often seen on constant speed machines. The frequency, magnitude and duration of these overload conditions represent serious fatigue loads on the turbine, and an over-sizing of structures to provide an acceptable life expectancy is required. The ability to limit and control torque is a primary driver in the application of variable speed technology to wind turbine systems.

<u>Operation of Two Speed Wind Turbines</u>

There are two economic performance issues associated with constant speed turbines. The first is the high fatigue loads discussed above associated with the steep torque-speed curve of the induction generator. The second is the poor aerodynamic performance due to operating the turbine rotor substantially off of its optimum tip speed ratio (TSR).[xv]

One approach to force a wind turbine to operate closer to its optimum TSR is to apply a two speed generator in place of the single speed generator shown in Figure 3. A two speed generator and its interconnecting method is shown in Figure 5.
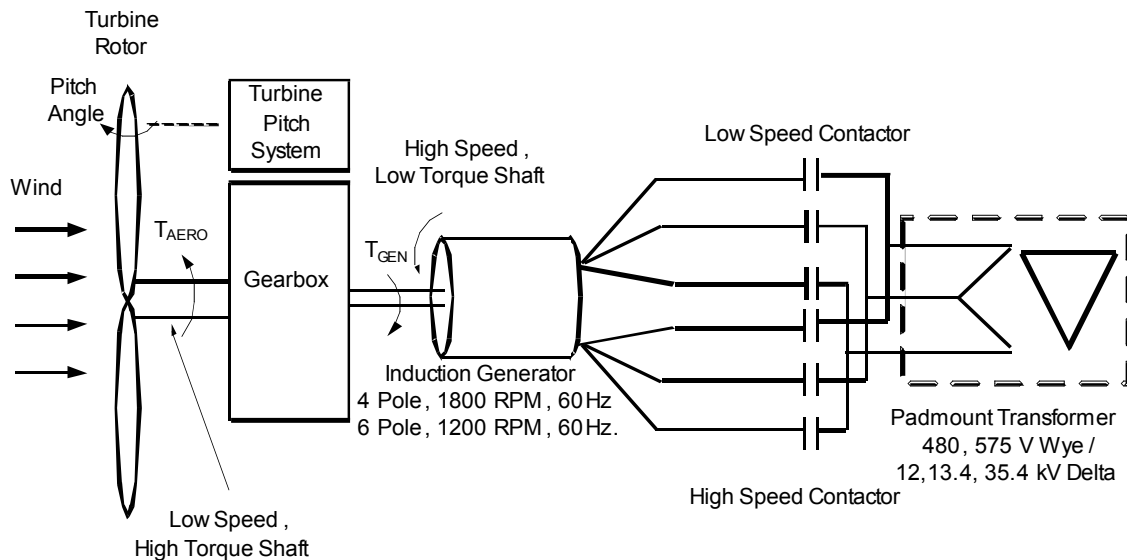
Figure 5. Turbine using a Two Speed Generator to Improve Aerodynamic Performance

The two speed generator is also an induction generator but with two windings. One winding is configured as a 6 pole stator, and the second winding is configured as a 4 pole stator. When the turbine is operating in low wind speeds, the low speed winding of the generator is connected through its corresponding contactor. As wind speed picks up, a threshold is crossed where the low speed winding is disconnected, and the high speed wind is connected. Good control practices require that there be a hysteresis, or overlap in the wind speed for which both windings could be connected. Judicious selections of the low speed-high speed transition point and the width of hysteresis band maximize the energy capture of a given turbine in a given set of wind conditions.

Since both connections represent an induction generator connected directly to the utility, the qualitative torque-speed curve shown in Figure 4 is applicable to

both windings. The curve shifts along the x-axis because the graph uses absolute speed, but the re-centered curves for the two synchronous speeds have similar shape. Note that when the generator is connected to the low speed winding, the pitch system is usually not active because wind speed is low and the turbine rotor is at full power pitch. The interaction between generator torque and the active pitch system however remains the same in high wind conditions and the two speed generator does not improve the high fatigue loads associated with rated power, turbulent wind conditions.

There is a penalty to applying two speed generators in wind turbines. Because the generator stator is now wound with two windings in the same (or similar) slots of a single speed machine, copper fill factors tend to be low for both windings and the efficiency of the generator can suffer significantly. Despite this, the improvement in aerodynamic efficiency more than offsets this reduction in efficiency. A slight variation on the two speed generator approach that deals with the low efficiency generator problem is the use of two distinct generators, one for low speed operation, and another for high speed operation. This allows each generator to be optimized for its own operation. Also, notice that while no PFC capacitors are shown in Figure 5, they are still required to reduce VAr consumption.

Variable Speed Wind Turbine Technology

In 1985 the Electrical Power Research Institute (EPRI) together with PG&E and US Windpower performed a study to identify possible improvements and advances to wind turbine technology which would make wind generated electricity more competitive with conventional fossil fuel technologies. An important outcome of this study was that variable speed technology produced two important advantages over constant speed machines. First, by varying the rotational speed of the turbine in direct proportion to the wind speed, the turbine could be made to operate at its optimal TSR throughout a wide wind speed range. This maximizes the energy capture of the turbine over a wide range and increases of 10% to 15% have been documented depending on wind regime. The second advantage of variable speed operation is that it allows precise control of torque and limitation of loads at rated and above rated wind speeds. Specifically, torque-speed characteristic at rated power could be arbitrarily defined, unlike the constant speed machine whose torque-speed characteristics were defined by the generator. These two factors were compelling and development of variable speed turbines began in earnest in the late 1980's and early 1990's.

The operation of a variable speed turbine can be understood by looking at Figure 6, which defines the torque, speed and pitch angle as a function of wind speed. Because these quantities can be arbitrarily defined in a variable speed machine a

graph for each quantity is required. In Figure 6-C, the turbine power curve is defined along with four commonly identified regions of operation. In Region I, the wind speed is below the turbine's cut-in level and the turbine does not operate. In Region II, the turbine rotor rotation speed varies in direct proportion to the wind speed. This is done so as to maintain a constant, optimal TSR for the turbine's rotor, optimizing energy capture in Region II. Also, notice that in Region II the torque is varied approximately as the square of the wind speed and rotor rotational speed. Because power is the product of torque and speed, the power shown in 6-C varies as the cube of wind speed or rotor rotational speed. Finally, in this region, the rotor pitch angle is held constant at the full power pitch angle; this is often at or near zero degrees.

Region III begins at rated wind speed where the turbine reaches its rated power output. Operation in Region III requires constant speed and constant torque operation as shown. In this region, speed is regulated by the pitch system, and increasing wind speeds result in the pitch angle moving towards the feather or 90 degree position. Finally, Region IV is defined as the high wind speed cut-out region. In this region wind speeds are high enough that the turbine must be taken off-line or damage to the turbine could occur.

An important distinction between constant speed machines and variable speed machines can be made by looking at Region III operation. In this region, the variable speed turbine runs at a constant speed just like the induction generator based turbine. The difference, however, is that the slope of the torque-speed characteristic is flat here, whereas in the constant speed machine the slope of the torque-speed characteristic is very high. It is this factor that reduces the loads on the turbine in Region III and allows for a reduction in turbine structural material. In Figure 6, the two objectives of variable speed machines can be seen readily. Improvement in aerodynamic efficiency by optimally tracking the rotor TSR in Region II, and loads reduction in Region III by controlling and limiting the generator torque, are both achieved.

Finally, it should be noted that Figure 6 represents the zero-turbulence case for wind speed. In real operation, wind turbulence causes slight modifications to the power curve shown, and creates momentary, fatigue loads which must be factored into the structural design of the turbine. Turbulence levels are defined in the International Electrical Committee (IEC) wind turbine standards for various wind classes.[xvi]
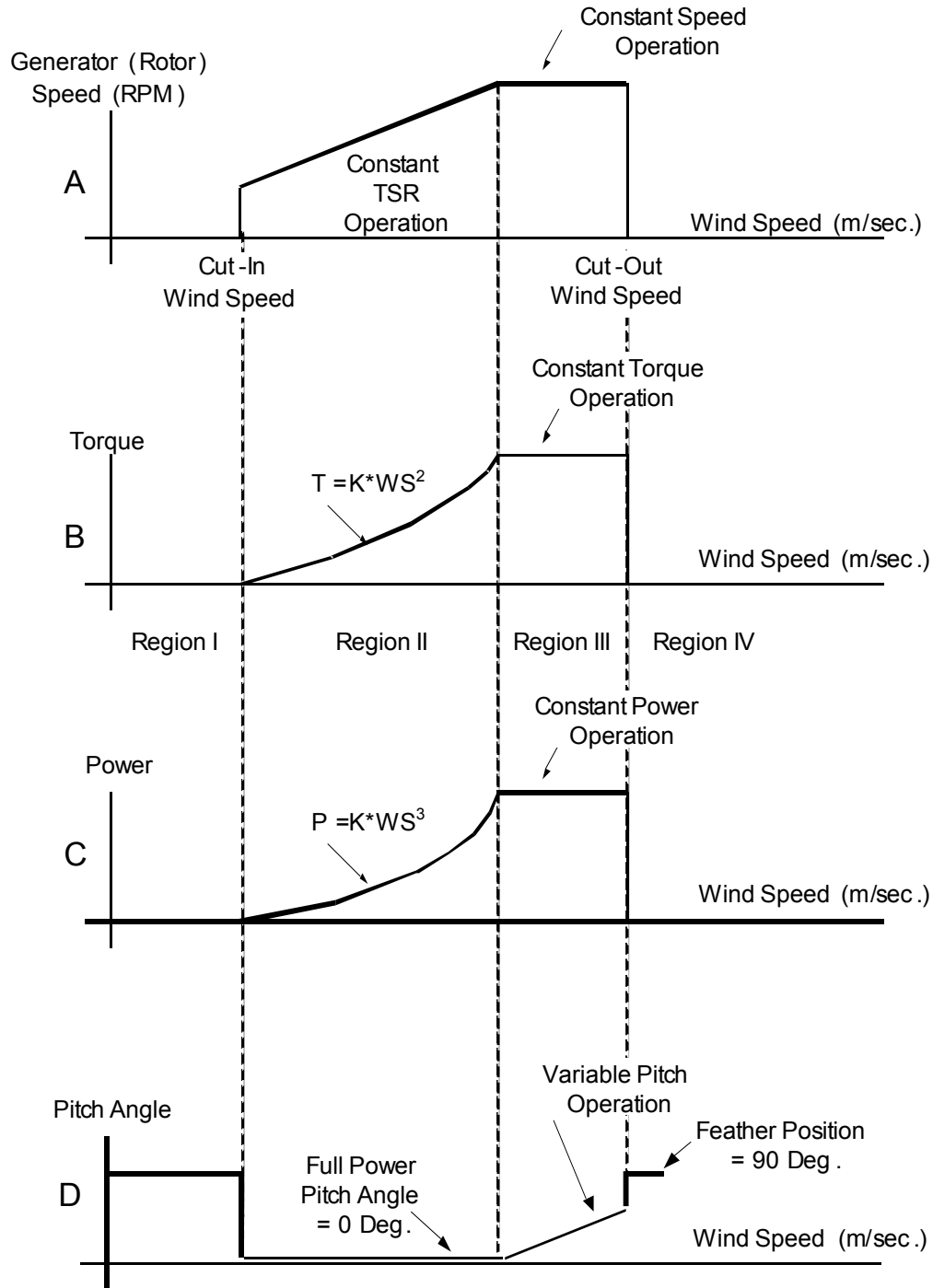
Figure 6. Torque-Speed-Pitch Relationships in a Variable Speed Wind Turbine

Doubly-Fed (Partial Conversion) Variable Speed Systems

The variable speed system shown in Figure 7 is a common approach to variable speed turbines which utilizes a doubly-fed induction generator with a power converter in the rotor circuit.
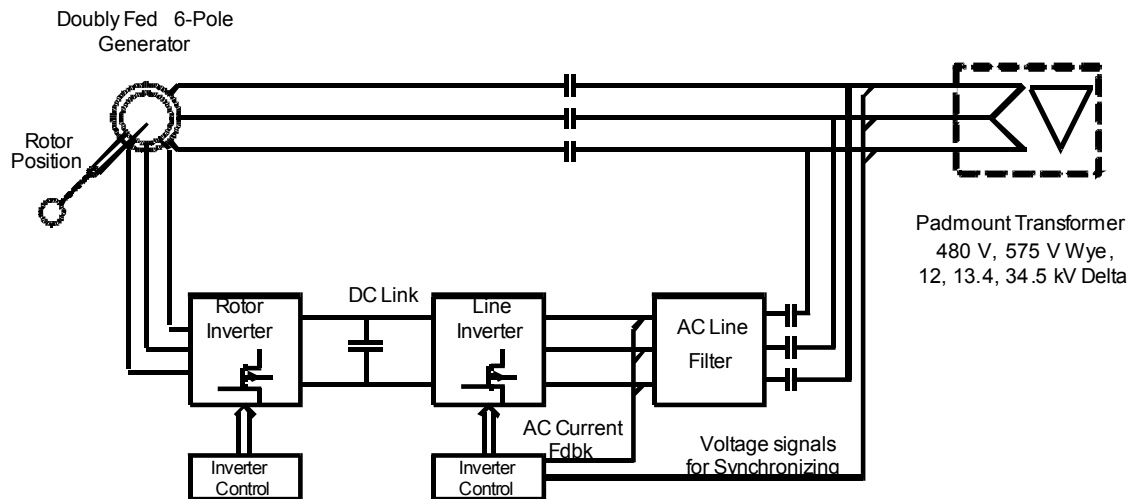
Figure 7. Doubly-Fed Generator and Power Converter for a Variable Speed Wind Turbine

The terminology "doubly fed" comes from the fact that the generator has two connections: one at the stator, and one on the rotor. The rotor only passes the slip power of the generator which is typically about 1/3 of the total power. For this reason, the converter does not have to be rated at the full rating of the generator. This is often cited as the principal attraction to this architecture. However, the generator must have slip rings and brushes to connect the rotating rotor to the stationary frame. The machine also has a three-phase, complex rotor winding and the machine tends to be more expensive than the simple squirrel cage rotor used in a constant speed machine.

Full Conversion Variable Speed Systems

Another approach to variable speed turbines is to use a full-conversion power electronic system. This is shown in Figure 8. The terminology full-conversion is used here because there is only one connection to the generator and all of the power is provided through this connection to the fully rated power converter for interconnection to the grid. Though both the full-conversion variable speed system and the partial-conversion doubly fed system follow the same control strategy described in Figure 6, there are significant differences in the electrical interconnect issues associated with the two systems.

Figure 8. Full-Conversion Variable Speed Generator and Converter System
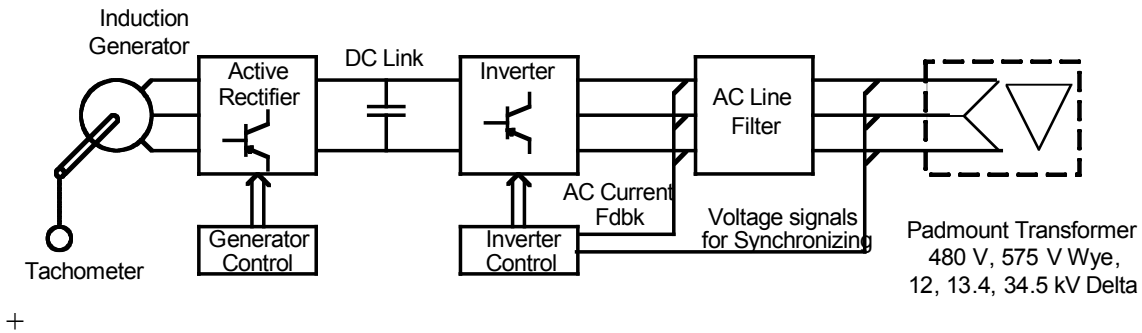
Two important differences can be seen by looking at the power factor of the generating system and how each system reacts to the new grid code requirements for grid disturbance immunity (refer to Section 6). Notice that in the doubly-fed case, there is a direct connection between the stator and the utility. This leads to undesirable stator dynamics in the event of a grid disturbance and can lead to excessive torque transients on the gearbox and turbine mainshaft. The full conversion system, on the other hand, completely decouples the generator from the utility, and dynamics during a grid disturbance can be better controlled. In the doubly-fed system of Figure 7, the stator power factor is typically set at unity. This is accomplished by controlling the magnetizing component of the rotor current through the converter. Leading and lagging power factors can be achieved for the system by over-exciting or under-exciting the rotor of the generator. When over-excited, the generator stator provides VArs to the utility similar to a synchronous machine. Under-excitation causes the absorption of VArs. By comparison, in the full-conversion system, the power factor or VAr level is determined entirely by the converter control system. VArs generated by the generator do not enter the DC link and the generator power factor is completely decoupled from the utility power factor. This type of system has the ability to run at an arbitrary leading or lagging power factor as long as the current capacity of the inverter is not exceeded.

Section 5 - New Transmission and Interconnection Issues for High Wind Penetration Scenarios

As discussed in Section 3, the lack of rigor in the interconnection planning process for California's major wind facilities in the 1980's was somewhat justifiable based on the low penetration levels. But with a four- to five-fold increase in the state's installed wind capacity projected by 2020 to meet RPS goals, many of the transmission system issues identified in Section 3 become of greater concern, and additional issues not even considered in the 1980's will

emerge. In this section, we outline the interconnection planning process, describe the types of planning studies involved in a wind plant interconnection, and identify the wind turbine technology aspects that influence the results of these studies.

The process of evaluating impacts of the interconnection of wind and other generation facilities in the state is well documented in existing California Independent System Operator (ISO) procedures,[xvii] which conform in large part to the FERC Standard Large Generator Interconnection Procedures.[xviii] Impacts are evaluated through three studies, with a finer level of detail and accuracy of financial and other impacts resulting from each successive study. These studies include:

> *Interconnection Feasibility Study*: An initial screening process is done to assess the feasibility of and provide a rough cost estimate of the interconnection facilities necessary to support the project. This estimate is supported through power flow and short circuit studies.

> *Interconnection System Impact Study*: The second study is intended to determine impacts of the proposed generating facility on the reliability of transmission system operator's (TSO) network. In addition to considering power flows and short circuit duties in the area of the project, the planner will investigate impacts on transient stability. This study may identify system upgrades needed to maintain reliability in locations that may be electrically quite distant from the project being interconnected. In contrast to the feasibility study, the wind turbine technology and associated wind plant controls to be employed are important considerations in this study.

> *Interconnection Facilities Study*: The final study is intended to produce a fine estimate (either ±10% or ±20%, depending on the project) of costs that must be incurred on the transmission system operator's facilities in order to accommodate the interconnection of the proposed generating facility.

The conclusions of these studies are drawn from the results of computer simulations using commercially available software tools[xix] that aid in determination of the impact of the proposed wind project, primarily through three forms of analysis:

> *Steady-State Analysis*: Steady-state analysis is performed through power flow simulations, normally with the wind plant dispatched at a power level expected to have maximum system impact (i.e., at rated output power) and with reactive power capabilities reflective of those of the proposed project. Power flow simulations are run for a list of system contingencies

(e.g., transmission line outages, generator outages, etc.) to determine system impacts under all realistic abnormal operating conditions. Two primary planning criteria are examined in a power flow study: thermal and voltage criteria. The thermal analysis is to verify that transmission lines, transformers and other equipment are not overloaded as a result of the project. The voltage analysis is to verify that the project does not have negative impact on voltage regulation at any buses in the transmission network. A third criterion that may need examination in some cases is contractually constrained power flow across control area interfaces. A sample output of a power flow simulation is shown in Figure 9. The bus voltages and line flows on the single line diagram are compared to specific planning criteria to determine whether system modifications for steady-state operation are necessary.
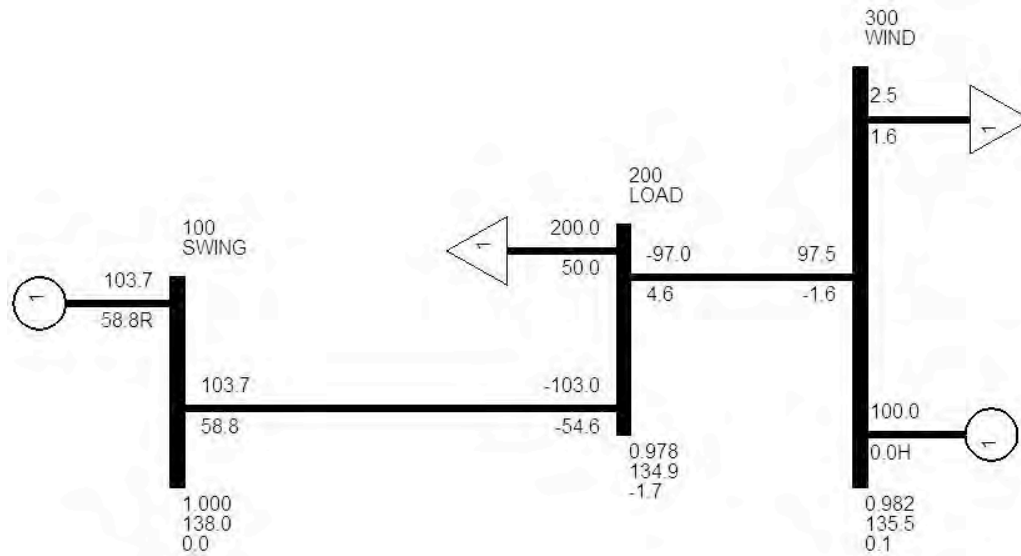
Figure 9. Sample Output of Power Flow Analysis for 3-Bus Transmission System

This steady-state analysis is largely independent of wind turbine technology. Real power injected at the wind plant's point of interconnection (POI) with the TSO is a function only of project size (and any real power losses on the project side of the POI). Reactive power capability may be provided by the wind turbines themselves, in the case of variable speed turbine technology, or by external means, such as capacitor banks or SVCs, in the case of constant speed technology. But from a steady-state perspective, both are modeled as reactive power injected at the POI in response to the voltage at some control bus, with appropriate adjustments made for reactive power consumption on the project side of the POI.

Short Circuit Analysis: Short circuit analysis is performed for both symmetrical and unsymmetrical faults on the transmission network in the

vicinity of the wind project to determine whether the addition of the wind generation results in equipment short-circuit withstand or circuit breaker interrupting capabilities being exceeded. Unlike the steady-state analysis, short circuit analysis is highly dependent on the wind turbine technology being used.

The electrical topologies examined in Section 4 have significant differences in their contributions to short circuits on the transmission system. Constant or dual-speed machines are capable of providing several times rated current to a short circuit in the first cycle, decaying within several cycles to a value dependent on the machine's terminal voltage during the period of time before the fault is cleared. The variable speed full conversion topology, in contrast, has inherent current limitation as a result of the power electronic interface with the grid. The converter current limit in these machines is typically set at a value slightly higher than nominal full load current so that the turbine can deliver rated power to the grid at some level of undervoltage, e.g., 10% below nominal. This current limit prevents the turbine from contributing more than normal load current into a short circuit on the transmission system. The variable-speed doubly-fed machine is the most complicated to characterize in a general sense with regard to its response to a short circuit. In the first fraction of a line cycle it will appear similar to a synchronous generator, supplying many times its rated current into the short circuit. However, due to magnetic coupling between the stator and rotor circuits, high voltages can appear at the terminals of the power electronic converter during this condition. To prevent damage to the converter, an electronic "crowbar" circuit is used to clamp this voltage.[xx] With the crowbar in operation, the rotor windings are shorted, and the machine behaves like the conventional induction generator used in the constant speed topology. The methods by which the crowbar is controlled during this transient vary considerably between different turbine manufacturers, and manufacturer-specific description is beyond the scope of this document. Crowbar control algorithms during this transient, though, have significant impact on the behavior of the machine during transmission system short circuits.

Transient Stability Analysis: Transient stability in its broadest sense may be described as the ability of a power system to return to a stable operating condition following a major disturbance such as a transmission line short circuit or a large generating unit trip.[xxi] Transient stability analysis is carried out by computer-based time domain simulation of the response of generator excitation systems, turbine governor systems and other controlled devices in the power system (switched capacitor and reactor banks, static VAr compensators, phase shifters, transformer load tap changers, etc.) to such disturbances. Planning criteria require that

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generator angular oscillations and voltage disturbances do not exceed specific values and are damped out within certain time periods, and, as in power flow analysis, these studies are run under various contingencies to verify that outages of specific transmission lines or generating units are considered. This analysis is focused on the time frame of from several line cycles to up to approximately one minute after the initiation of the disturbance. An example output from a transient stability simulation is shown in Figure 10, below. In this case, the major disturbance (a 3-phase remote bus fault) occurs at time t = 1.0 second, and oscillations associated with the generator under study are damped out within approximately 10 seconds, indicating good transient stability.

Figure 10. Example of Transient Stability Simulation Output
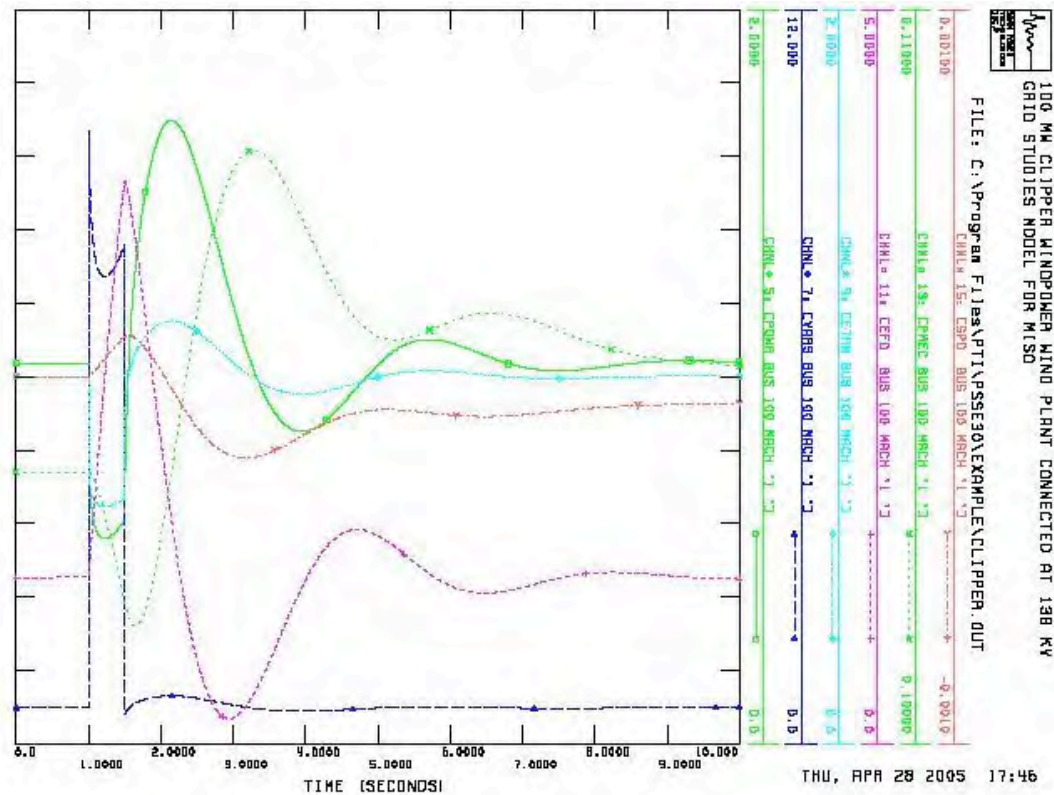
Transient stability is one of the major drivers behind recent low voltage ride-through requirements for wind turbines (see Section 6). If a large wind plant were to unnecessarily trip off line in response to a remote transmission line fault, an additional disturbance is created (the loss of generation) which further erodes stability margins for the original event.

The dynamic response of wind turbines to transmission system disturbances is highly technology dependent, and a major obstacle in performing accurate transient stability analyses is the lack of suitable dynamic models of the various wind turbine types. While turbine manufacturers have very accurate dynamic models of their machines for their own design purposes, the tools used for dynamic simulation by the turbine designer are very different from those used by the transmission planner. The turbine designer is concerned with phenomena occurring well above and well below the nominal power system frequency, so EMTP and SPICE derivatives[xxii] are better suited to his needs. These models are not compatible with the positive sequence phasor time-domain tools, such PSLF and PSS/E, used by the transmission planner in his dynamic simulations. While the turbine manufacturers are working with the TSOs to adapt their existing dynamic models to forms that are useful for transmission planning purposes, there are still obstacle to overcome, including:

> *A lack of model validation procedures*. Field measurement data to verify and validate the turbine models that do exist is lacking. Most turbine manufacturers have validated their transmission planning models only against their EMTP models. While procedures to validate specific dynamic responses (e.g., for low voltage ride through) are under development,[xxiii] standardized procedures that one would use to validate exciter or governor models for conventional power plants do not currently exist for wind turbines.

> *Agreement on the level of complexity necessary*. There is still debate with respect to the level of detail and the order of the models necessary for planning purposes. Some models are focused on wind turbine dynamics, and include effects such as turbine mainshaft oscillation modes that would not even be seen at the POI with TSO for a multi-turbine wind plant.[xxiv] Other models are geared to the large wind plant, and recognize that higher order stochastic effects do not impact the TSO.[xxv] Further debate continues on whether wind disturbances, in addition to grid disturbances, should be considered in system impact studies.

> *Proprietary turbine control algorithms*. Turbine manufacturers are reluctant to provide modeling data which includes proprietary control algorithms without non-disclosure agreements. This makes it difficult for the transmission planner to evaluate wind plant impacts in the early stages of a project where the turbine manufacturer may be unknown.

WECC is taking a leadership role in addressing these issues by developing a set of generic, reduced order wind turbine models, in cooperation with the wind industry, for each of the electrical topologies described in Section 4.[xxvi] This will eliminate the proprietary information concerns, as turbine manufacturers will only supply a set of input parameters (time constants and gains) for the generic model that best represents how their products will respond to grid disturbances. This is, in essence, how conventional generation has been modeled for many years; with standardized (developed under WECC or IEEE standards), rather than manufacturer-specific proprietary models. This will allow the planner to do his job at the system impact study stage, with sensitivity analyses performed using more detailed manufacturer-specific models in the later stages of the project.

Other analyses, generally not considered in an individual wind plant system impact study, but which must be addressed on a system-wide level for high penetration scenarios, include small signal dynamic stability and voltage stability. Small signal dynamic stability is the ability of the power system to maintain a fixed frequency for small disturbances, such as normal increases or decreases in load. This analysis is normally done by linearizing the power system state equations and performing eigenvalue analysis on these state equations to determine the frequency and damping coefficients of the system's natural modes of oscillation. In the western part of the US, including California, synchronous generators are equipped with power system stabilizers (PSS), control systems that act on the generator excitations systems to effect torques that dampen these modes. Present-day wind turbines are not equipped with PSS capabilities. In one recent study, however, it was shown that for some variable speed wind turbine types, damping of inter-area oscillation modes may be improved by increasing wind penetration levels in the case where the synchronous generation being supplanted is not equipped with PSS.[xxvii] To date, similar studies that consider PSS-equipped synchronous generation being replaced with wind generation have not been undertaken.

While the stability of network voltages is a key criterion in a transient analysis, the term voltage stability has recently evolved to describe a longer term dynamic phenomenon, which in the case of voltage instability can result in a gradual collapse of system voltage over a time period of minutes to hours. The root cause of this gradual voltage collapse is often a mismatch in local reactive power consumption and production which occurs as a result of changes in load or generation and/or a contingency such as loss of a transmission line or large transformer or generating unit that causes a portion of the remaining transmission system to be operated near its steady state stability limit, which can be below its thermal limit for long transmission distances.

Voltage stability margin is normally presented in the form of P-V curves which plot the load bus voltage as a function of power that may be transmitted over a transmission line at a given load power factor. An example is shown in Figure 11, where P-V curves have been developed for three different load power factors for a given transmission line reactance. In each case, the "nose" of the P-V curve represents the limit between stable and unstable operation. An attempt to transmit power in excess of this limit will result in voltage collapse. For instance, in Figure 11, for a unity power factor load, any increase in load beyond one per unit power will result in voltage collapse. However, were the load power factor change to 0.9 leading through reactive power compensation at the load bus, the load could increased to 1.6 per unit before voltage collapse occurs.
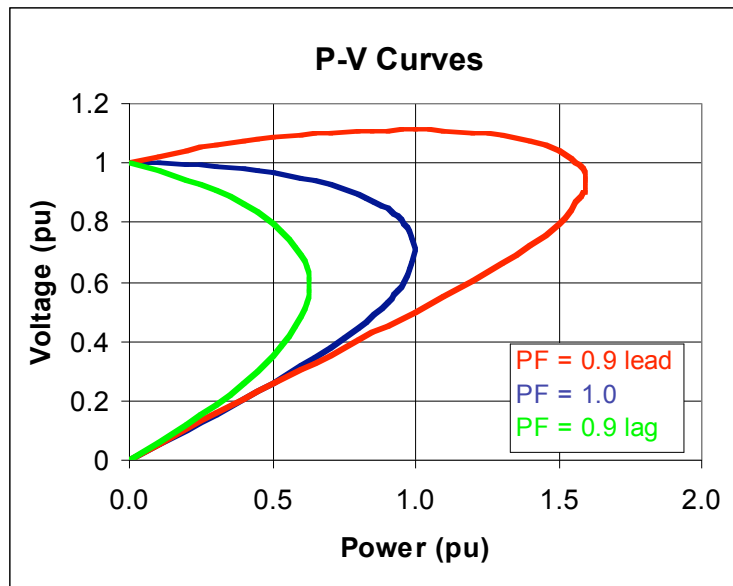
Figure 11. PV Curves for Voltage Stability Analysis at a Load Bus

Similar P-V curves may be developed for wind generation being transmitted to remote load centers to assess voltage security. This tool may aid in determination of reactive power compensation requirements to meet voltage stability margin planning and operating criteria, and is another example of a system impact that is highly dependent on the wind generation technology employed. Constant speed induction generator based turbines using mechanically switched capacitors may aggravate voltage instability since the reactive power production of the capacitors fall as the square of the fall of line voltage and since their control is relatively slow and coarse (limited to the fixed steps of capacitance that may be switched in or out of service). On the other hand, variable speed turbines with reactive power control capabilities may offer continuous control capability up to the current limits of their power electronic converters. In either case, voltage stability margins may be improved by the

application of STATCOMs, SVCs or synchronous condensers at the wind plant level where the reactive power capabilities of the turbines themselves are insufficient to maintain adequate security.

Section 6 - New and Evolving Wind Power Interconnection Standards and Procedures

Restructuring of the electric power industry and the elimination of the traditional vertically integrated utility is having significant impact on the wind power interconnection process. In the 1980's, wind project interconnection requirements were negotiated on a project-by-project basis between the utility and the project developer. The low penetration levels represented by these early developments may have created local area transmission problems, but they had no impact on neighboring utilities or on regional reliability. In today's regulatory environment, bilateral agreements between utilities and developers have been replaced with standardized processes implemented under the jurisdiction of CAISO and the Federal Energy Regulatory Commission (FERC). This trend towards standardized interconnection processes has occurred not only in California and the US, but throughout much of the rest of the developed world. In this section, we summarize the interconnection standards that have evolved from restructuring and examine their impacts on wind power technology choices.

The evolution of national interconnection standards, also referred to as "Grid Codes", had its beginnings in Europe, stimulated by the electric power industry restructuring combined with strong incentives for renewable energy implemented in the late 1980's and early 1990's, a decade earlier than these trends emerged in North America. While work on these interconnection standards began in the late 1990's, it was not until 2003 that Germany's TSOs published their standard.[xxviii] This was quickly followed by Denmark in 2004[xxix] and Spain in early 2005.[xxx] These were important developments in that these three countries represent the first, fourth and second largest markets, respectively, for wind power in the world.[xxxi]

North America, while slow to start relative to Europe, has been quick to catch up. WECC, home to a significant portion of the continent's wind resources, and with transmission challenges unrelated to wind due to the wide geographic separation between the population centers of the West, was the first entity in North America to apply significant resources to this issue. NERC and the other reliability councils soon followed. The most recent result of these standardization efforts is a recent FERC order,[xxxii] which codifies interconnection requirements for wind energy on a national basis.

While each of these national grid codes has aspects that are unique to the particular countries' concerns,[xxxiii] there are components that are common to each of them, including:

> *Low Voltage Ride-Through Capability*: To support transient stability during major transmission system disturbances, wind plants are required to "ride through", or stay connected to the network and able to deliver power, during low voltage transients of a given magnitude and time duration. This is a major departure from the earlier philosophy of tripping wind generation off line for any grid disturbance, and has resulted in significant design changes to wind turbine control systems. These requirements are often expressed through curves of voltage versus time. An example from the German E.ON-Netz standard is shown in Figure 12. In the areas of Germany served by E.ON-Netz, the wind plant must stay on line for any point above the curve. This implies that the wind turbine technology chosen for the plant must be capable of operating continuously at 80% of nominal voltage, and must not trip off line for transient voltages as low as 15% of nominal for durations up to 150 ms. There is a wide range on requirements, which vary from country to country, on the details of how the wind turbine is to behave during this transient. All require the machine to be on line and ready to supply power immediately after the transient has passed. Some require that the wind plant supply reactive power to the network during the event, while others require only that reactive power not be consumed during the transient. Some are explicit about whether these requirements apply to three-phase symmetrical voltages as well as for unsymmetrical voltages (as may be present during a single phase-to-ground transmission line fault), and others are silent on the issue.
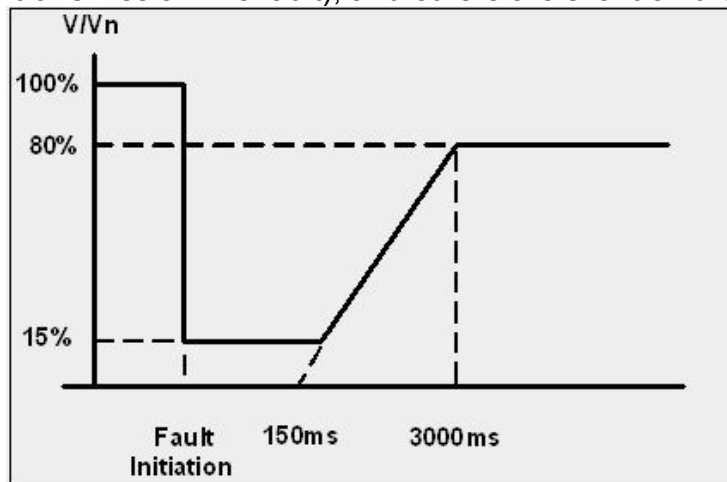

Figure 12. E.ON-Netz Low Voltage Ride-Through Requirement for Wind Turbines

Reactive Power Support: To contribute to voltage regulation, wind plants are required to have some level of reactive power management capability. This can range from a requirement to provide sufficient reactive power compensation to provide for the plant's own reactive power consumption (within some bandwidth) to providing fast dynamic voltage control at the wind plant's POI with the TSO. As described in Section 5, the methods by which these requirements are met is highly technology dependent, with variable speed turbines having inherent reactive power control capabilities and constant-speed machines requiring external devices such as switched capacitor banks or static VAr compensators. Germany's requirements for reactive power support from wind plants are the most comprehensive. They require that the TSO have the capability to control the wind plant's power factor, dispatch the plant's reactive power, or have the wind plant perform closed-loop voltage control at the POI; essentially, the wind plant must behave like a traditional central station synchronous generator in this regard. The FERC requirements for the US are, in fact, not standardized requirements at all. The wind plant is required to have the capability to operate over a range of power factors from 0.95 over-excited (sourcing reactive power) to 0.95 under-excited (absorbing reactive power), but only if this is determined to be required for reliability reasons in the interconnection system impact study (see Section 5). Further, the issue of whether reactive power control is to be static (e.g., constant power factor) or dynamic (voltage control) is to be determined though the interconnection studies.

Supervisory Control and Data Acquisition (SCADA): Wind plants are required to have some degree of real-time data exchange with the TSO. In Denmark, very well defined data communication protocols have been established for this purpose. In addition, the installation of fault recorders both at the individual wind turbine and the wind plant's POI with the TSO is mandatory in new Danish wind plants. By contrast, the FERC requirements in the US mandate only that wind plant SCADA systems be present and that the TSO have access to real-time plant data via telemetry, but leaves details on data requirements and communication protocols to the contracting parties.

The salient features of these grid codes in the world's four largest wind markets are summarized in Table 1, below.

	Germany	*Denmark*	*Spain*	*USA*
Low Voltage Ride Through				
Fault Types	3-phase, only	Any	Any	Any
Depth (% of nominal) and Duration of Dip	15%, 150ms	25%, 100 ms	20%, 500 ms	0%, 150 ms
Recovery Time and Voltage (% of nominal)	To 80% in 3s	To 75% in 1s	To 80% in 1s	Specified project-by-project
Feed the Fault?	Yes	Yes	Yes, within 150 ms	No
Reactive Power				
Static Power Factor Range	0.95 under-excited to 0.95 over-excited	Greater than 0.995 at all times	Not specified	0.95 under-excited to 0.95 over-excited (if necessary)
Control Mode Capability	1) Static power factor, 2) static reactive power, and 3) dynamic voltage control	Static power factor, only	Must source reactive power following faults, only	1) Static power factor or 2) dynamic voltage (if necessary)
SCADA				
Real Time Telemetry	Yes	Yes	Yes	Yes
Fault Recorders	No	Yes	No	No

Table 1 Summary of Grid Code Requirements in Countries with Largest Wind Power Capacity

Section 7 - Future Wind Turbine Technology Enhancements for Improved Grid Compatibility

In North America, wind projects to date have been largely exempt from providing transmission system ancillary services. Wind turbine manufacturers and wind plant developers in the current low penetration scenario are concentrated on producing at the lowest cost the only service they are currently being compensated for – electric energy. While wind technologies are capable of providing a variety of ancillary services, market mechanisms have not yet been developed that provide sufficient incentive for a wind plant owner to remove his focus from maximizing kW-hr production. In higher penetration areas (e.g., in western Denmark, where wind penetration approaches 100% during light loading and windy conditions[xxxiv]), government regulation, in the form of restrictive grid codes, has provided that incentive.

In this section, we examine wind turbine technology enhancements currently under development to address current or anticipated grid code restrictions and/or ancillary service opportunities. The technology enhancements include:

Real Time Curtailment: This capability would allow a TSO to reduce the average power output of a wind plant in real time through SCADA to manage the deliverability and reliability issues discussed in Section 5 under high-wind, low-load system conditions. Curtailment capability can be envisioned at two levels, one at the wind plant level and the other at the wind turbine level. At the wind plant level, current wind plant communications and control technology already support a gross level of power control by allowing for individual turbines to be taken on and off line to manage overall wind plant output. A finer level of curtailability could be implemented at the wind turbine level by real time control of the turbine's maximum power output. Pitch regulated machines may be adapted to include this capability through control system modifications, and, in fact, this feature is already commercially available from turbine manufacturers supplying to the Danish market, where the latest grid code revision set strict requirements for controllable power regulation over a range of 20% to 100% of rating at the wind turbine level. This requirement has effectively eliminated stall regulated turbines from the Danish market,[xxxv] as they are unable to shed power in high winds to meet this new requirement. In the case of pitch regulation, a turbine's power curve could be modified in real time by shifting the transition between Region II and Region III operation (refer to Section 4), as shown in Figure 13.
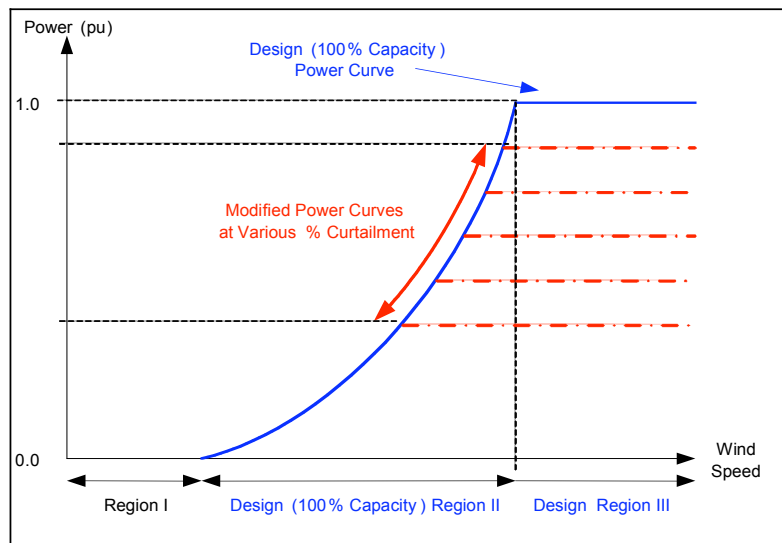

Figure 13. Real Time Curtailment Via Pitch Control

With tight control over maximum power output, wind plants could technically contribute to spinning reserve and to frequency regulation (i.e., by "droop" control) by being operated at some average power level below that which is available for the prevailing wind conditions at any instant in time. Whether a resource with a zero marginal cost of energy would be applied in this manner is another question.

Ramp Rate Control: While localized power fluctuations due to stochastic turbulence within a wind plant have been demonstrated to have minimal transmission system impacts, longer term changes in wind speed that affect the average value of power production at the POI with the TSO is an increasing concern in high penetration scenarios. Unless wind is contributing to frequency regulation and spinning reserve, any balancing of wind power output relative to load is performed by other power plants on the network. Many of these power plants, particularly steam plants, have long thermal inertia constants that limit the rate at which they can be ramped up or down in power output. At best, these thermal plants will operate less efficiently; at worst, frequency stability could be jeopardized.

While ramp rate control is in direct conflict with current wind turbine design goals of optimizing energy production, it is technically possible through a combination of wind plant and wind turbine control strategies, and is under consideration as part of RPS implementation in other states. Positive ramp rate control (i.e., limiting the rate at which power increases during increasing wind speeds) is theoretically achievable with any pitch regulated turbine, and such requirements have already made their way into some of the European grid codes referenced in Section 6. Negative ramp rate control during rapidly falling wind speeds is more difficult, though variable speed turbines have some limited kinetic energy storage that could be applied to this end.

Black Start: Variable speed turbines with self-commutated converters have inherent black start capability, as long as a backup source for control power is available at the turbine. Restoration of portions of the transmission network following a major disturbance is a theoretical possibility with this class of turbines, and start-up times and ramp rates to full power are on the order of seconds – much faster than thermal generation. The intermittency of the resource, will in most cases, however, make wind a poor candidate for this function.

Reactive Power Control in No-Wind Condition: Wind power plants have a significant advantage over conventional synchronous generator based power plants in that they can source or sink reactive power even during periods of time when the wind turbines themselves are not producing any active power. Thus, they are available to provide voltage regulation support regardless of wind condition. For all of the commercially available variable speed wind turbine technologies, control of reactive power is decoupled from control of generator torque (active power production), so there is no requirement that the turbine be active to provide this ancillary service. For constant speed machines, the reactive power management equipment (capacitor banks, SVCs, STATCOMs) are even physically decoupled from the turbines, and available to provide voltage support independent of the state of the turbines. The authors are not aware of any current applications where market mechanisms have provided financial incentives to capitalize on this capability of modern wind plants, but it has been recognized as a potential system benefit in other wind penetration studies.[xxxvi]

Table 2, below, relates the wind turbine technology enhancements discussed in this section with the potential problems from Section 5 that they address.

	Transmission Congestion	Transient Stability	Dynamic (Small Signal) Stability	Voltage Stability
Remote Curtailment	✓	✓	✓	✓
Spinning Reserve		✓		
Frequency Regulation			✓	
Ramp Rate Control			✓	
"No-Wind" VAR Control		✓		✓

Table 2. Summary of Technology Enhancements to Address Transmission Integration Issues

Glossary

The following acronyms are used in this report:

CAISO   California Independent System Operator

CPUC   California Public Utilities Commission

CWEC   California Wind Energy Collaborative

DOE   Department of Energy

EPRI   Electric Power Research Institute

FERC   Federal Electric Regulatory Commission

IAP   Intermittency Analysis Project

IEC   International Electrotechnical Commission

IEEE   Institute of Electrical and Electronic Engineers

NEC   National Electrical Code

NERC   North American Electric Reliability Council

PFC   Power Factor Correction

PG&E   Pacific Gas and Electric Company

PIER   Public Interest Energy Research

POI   Point of Interconnection

PSS   Power System Stabilizer

PURPA   Public Utility Regulatory Policy Act

QF   Qualifying Facility (under PURPA)

RPS   Renewable Portfolio Standard

SCADA   Supervisory Control and Data Acquisition

SCE   Southern California Edison Company

SO4   Standard Offer 4

SVC   Static VAr Compensator

TSO   Transmission System Operator

TSR   Tip Speed Ratio

UPS   Uninterruptible Power Supply

VAr   Volt-Ampere Reactive

WECC   Western Electric Coordinating Council

Footnotes

[i] Jackson, K. J., "Wind Power Generation Trends", Report CWEC-2003-01, California Wind Energy Collaborative, October 2002.

[ii] Yen-Nakafuji, D., "California Wind Resources," Report CEC-500-2005-071-D, California Energy Commission, April 2005.

[iii] P. Gipe, *Wind Energy Comes of Age*. New York: John Wiley & Sons, 1995.

[iv] California Wind Resource Maps, California Energy Commission. Internet: http://www.energy.ca.gov/maps/wind.html.

[v] Additional wind projects, accounting for less than 1% of total state capacity, were installed in the Pacheco Pass, southern Solano County and eastern San Diego County during this period.

[vi] P. White, P. Gipe (1993, May 27), "Repowering California Wind Power Plants", Comments by the American Wind Energy Association on Repowering California's Wind Industry Prepared for the California Energy Commission's 1994 Biennial Report. Internet: http://www.wind-works.org/articles/Repower.html.

[vii] Putnam, R.G, "Assessment of California Wind Plant Operating Experience," Proceedings of Conference on Integration of Wind Power Plants in the Environment and Electric Systems, European Wind Energy Association, October 1996.

[viii] One of the steps taken by SCE to avoid forced bankruptcy in the fallout of the state's deregulation of the electric power industry was to temporarily suspend payment to many QFs, including wind power providers. This was a precursor to QF contract renegotiations that eventually eliminated the so-called "curtailment fees" for undelivered wind energy.

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[x] "Protection Aspects of Multi-Terminal Lines", Special Publication of the IEEE, IEEE Power Engineering Society Power System Relaying Committee, Publ. No. 79 TH0056-2-PWR, pp. 1-18, 1979.

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[xiii] McNerney, G., Richardson, R.; "The statistical smoothing of power delivered to utilities by multiple wind turbines", IEEE Transactions on Energy Conversion, Volume 7, Issue 4, Dec. 1992, pp. 644 – 647.

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[xv] Jackson, K. J., "Wind Power Generation Trends", Report CWEC-2003-01, California Wind Energy Collaborative, October 2002.

[xvi] IEC Standard 61400-1, Edition 3, Wind Turbines - Part 1: Design Requirements, International Electrotechnical Commission, 2005.

[xvii] *Large Generator Interconnection Procedures of the California ISO.* Internet: http://www.caiso.com/docs/2005/08/30/20050830160722515.pdf.

[xviii] FERC Order No. 2003-C, *Large Generator Interconnection Procedures.* Internet: http://www.ferc.gov/industries/electric/indus-act/gi/stnd-gen/2003-C-LGIP.doc.

[xix] In California, as in much of the rest of the WECC, General Electric's PSLF software is the primary tool used for these simulations.

[xx] Niiranen, J., "Voltage dip ride through of a doubly-fed generator equipped with an active crowbar", Proceedings of 2004 Nordic Wind Power Conference, Gothenburg, Sweden, March 2004.

[xxi] P.M. Anderson, A.A. Fouad, *Power System Control and Stability.* New York: IEEE Press, 1994.

[xxii] Examples of EMTP (Electromagnetic Transients Program) and SPICE (Simulation Program with Integrated Circuit Emphasis) derivatives are commercial software packages such as PSCAD, PSIM and SABER.

[xxiii] IEC Standard 61400-21, Draft Edition 2, Wind Turbines - Part 21: Measurement and assessment of power quality characteristics of grid connected wind turbines, International Electrotechnical Commission, 2005.

[xxiv] Miller, N.W., Sanchez-Gasca, J.J, Price, W.W., "Dynamic Modeling of GE 1.5 and 3.6 Wind Turbine-Generators," GE Power Systems Energy Consulting, Version 3.0, October 2003.

[xxv] Behnke, M.R., Muljadi, E., "Reduced order dynamic model for a variable-speed wind turbine generator with synchronous generator and full power conversion topology", Proceedings of 2005 International Conference on Future Power Systems, Amsterdam, Netherlands, November 2005.

[xxvi] Zavadil, R., Miller, N., Ellis, A., Muljadi, E.; "Making connections: wind generation challenges and progress", IEEE Power and Energy Magazine, Vol. 3, No. 6, November 2005, pp. 26 – 37.

[xxvii] Sanchez-Gasca, J.J., Miller, N.W., Price, W.W., "A modal analysis of a two-area system with significant wind power penetration", Proceedings of 2004 IEEE PES Power Systems Conference and Exposition, October 2004, pp.:1148 – 1152.

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[xxxi] Ireland, Finland, Sweden and Great Britain also implemented grid codes during this time period, but do not have significant wind markets relative to Germany, Spain, the US and Denmark.

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